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Article

An Overview of Distributed Control Systems: Advances in Architecture, Stability, and Control

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Abstract: - As automation technology in large and complex engineering facilities has rapidly advanced, the distributed control system (DCS) has become widely used in a variety of industries, including advanced machining tools, aircraft engines, electro-hydraulic powered equipment, automobile control systems, industrial robots, and power systems. It is important to look at recent advancements and find DCS techniques, given the growing research trends in these areas. This review paper provides a concise summary of these systems, including their configurations, challenging issues, and approaches. This review paper initially analyzed the development of DCS, its functionality and operation, its architecture, and its fundamental components. The uses of DCS in diverse industrial and infrastructure settings are elucidated, followed by a discussion on the stability analysis of DCS. The benefits and drawbacks of DCS are further elucidated through an analysis of current research. The review study ultimately closes with prospective enhancements derived from existing material, which will aid researchers in advancing their work.
Keywords: Distributed Controller System (DCS), controller system configurations, applications of DCS, features and working process, stability analysis, centralized and decentralized systems.

1. INTRODUCTION

Large-scale systems with linked subsystems have been established as a result of technological advancements in manufacturing and industrial processes as well as economic considerations. Huge-scale plants consist of several subsystems and subprocesses that are typically scattered across huge geographic areas. Controlling these plants requires measuring geographically dispersed variables and controlling many devices located far apart [1]. Industrial control systems (ICS) can be classified into two types: programmable logic controllers (PLCs) and distributed control systems (DCS). DCS, or digital automated ICS, uses geographically dispersed control loops to operate machinery, factories, and control regions. DCS strives primarily to increase reliability, safety, and economy by regulating industrial processes [2].

In the structure, DCS controllers are dispersed both geographically and operationally. To carry out all required control functions for a large plant or process, they communicate with each other, the supervisor, and operator terminals. DCS works best in a plant with lots of continuous control loops, specific control functions, process variables, and alerts [3]. The DCS is sometimes referred to as the “central nervous system” of various power plants because it controls the operation of around 10,000 units and processes a wide range of operational circumstances. DCS is characterized by its robust

capacity for self-diagnosis, adaptability to growth, and simplicity of implementation [3]. DCS has garnered considerable interest over the past decade, primarily because of its anticipated present and future applications. These applications include industrial process control [4], mobile vehicles [5], surveillance [6], oil and gas pipelines [7], and electric power grids [8].

In industries such as pharmaceutical processing facilities, water and wastewater treatment plants, oil refineries, and chemical manufacturing plants, DCS is utilized to regulate production systems within a specific geographic region. Typically, these systems employ discrete elements or process control [9-10]. The evolution of control systems should be examined to understand DCS. This covers the structural elements, concepts for implementing the system, and the motivations behind this advancement. This will enable us to comprehend how decision-making, information flow, and process control have changed over time.

The rest of the paper is organized as follows. The goal of this review study is described in Section 2. A detailed explanation of the review approach is given in section 3. Section 4 describes the general configurations of control systems. The fundamentals of DCSs are covered briefly in Section 5 from four angles: evolution, structure and operation, operating principle, and key feature. Section 6 examines the recent DCS implementation in various power plants. Section 7 provides the stability analysis of DCS. The major benefits and limiting factors of DCS are discussed in Section 8. Section 9 discusses potential future research directions. Lastly, Section 10 presents the conclusions.

2. REVIEW OBJECTIVES AND MOTIVATION

At the core of industrial control systems (ICSs), such as distributed transportation networks, distributed electrical power systems, smart grids, remote surgery, cellular phone networks, and industrial and manufacturing systems, distributed control switches (DCSs) are becoming more and more important. This is due to the Internet's quick development and widespread use, embedded systems, wireless communication technologies, and cutting-edge control techniques. Despite the fact that the systems and applications mentioned above demonstrate some of the advantages and applications of DCSs, no thorough theory presently exists to sufficiently describe the synthesis and analysis of these kinds of systems. It is evident that any progress made along this research path will inevitably enhance knowledge of the extensive theory and numerous applications of DCSs.

This study provides a brief assessment of DCSs, concentrating on current advances, problems, techniques, and future potential. Furthermore, the different applications of the DCS to the control of power systems, oil and gas, water treatment plants, and microgrid model predictive control are discussed. This will assist designers in determining how DCS has evolved over time in terms of process control, information flow, and decision making. It will also aid DCS engineers in providing technical support to clients and updating systems to meet evolving plant and process requirements.

3. REVIEW METHODOLOGY

This section briefly discusses some of the research questions related to this review paper and the search method used to choose different journals or research papers to make a review of various existing models.

3.1 Research queries

Some of the research queries relevant to this review are mentioned here.

Q1: What is the difference between DCS and PLC?

Q2: What is the working process and operations of the DCS?

Q3: What are the applications of DCS, and what is the purpose of controllers in those applications?

Q4: What kind of stability analysis is performed for DCS to check the behaviours of the system over time?

Q5: What are the advantages and disadvantages of DCS?

3.2 Search strategy

Both manual and automatic searches are part of the search strategy; an automatic search proved useful in locating primary research and acquiring a broader perspective. As a result, the review is enlarged to include new findings. The study's references were found using a human search approach following the automated search process. Standard databases like IEEE Explore, ISI Web of Knowledge, Elsevier, and Springer are used for automatic search and yield the most relevant research. Despite the abundance of material found in magazines, working papers, newspapers, books, and blogs, these sources were not chosen for this review article because the topics they address are not put through a review process, which makes it difficult to accurately confirm their quality. Generic keywords that were derived from the study's title and our research questions were used to search the research articles. Many relevant papers are extracted as possible from the main keyword list by using this search approach. Also, the search is enabled for any combination of DCS concepts, such as "Distributed Controller System (DCS)," "applications of DCS," "operations and features of DCS," etc. The objective of the data analysis phase of the retrieved research articles was to ascertain their relevance to the research questions, following the usage of search strings to gather primary data. An automatic search was carried out initially, followed by a personal search to ensure that nothing was neglected. This was accomplished using both forward and backward referencing.

4. GENERAL CONFIGURATIONS OF CONTROL SYSTEMS

Numerous control architectures, such as distributed, decentralized, and centralized control systems, have been proposed [11]. Figure 1 depicts three general layouts for the control system.

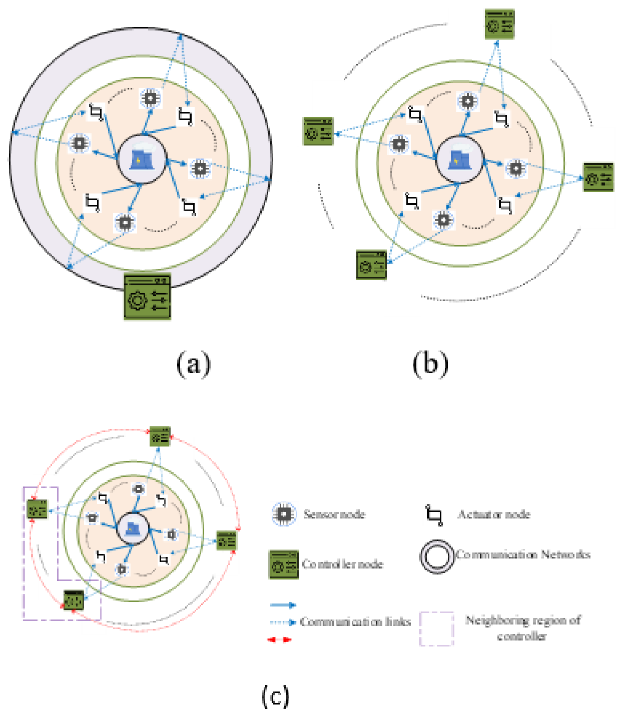


Figure 1 General configuration of control systems (a) Centralized (b) Decentralized (c) Distributed

Centralized configuration**:** In this architecture, the centralized controller, which incorporates a central processing unit for data fusion, receives sensed measurements (system output, system state, or reference input) from all sensor nodes, as illustrated in Figure 1 (a). The centralized controller benefits from comprehensive system knowledge. In order to produce fused data that may be used to calculate control execution, appropriate data fusion methods are required. Actuators then receive these control executions and use them to control the system. In this scenario, a single feedback loop control system was examined. A specialized sensor node was required to take all measurements, which were then sent as a single packet to a remote controller node. Finally, a particular actuator node receives a return command for the control execution. The main benefit of this centralized system is that control performance can be greatly enhanced because measurement data is accessible on the controller side. The centralized setup has many disadvantages, including the controller's vulnerability to failure, the high cost of gathering data from individual sensor nodes, greater processing stress, and limited application scope in modern control systems with distributed sensing.

Decentralized configuration: Figure 1 (b) shows that each controller node can make its decision entirely based on the controller's local information. As such, dispersed controller nodes might not be able to communicate with nearby nodes, even in the event that the entire system is working toward the same goal. Control systems with multiple feedback loops may be easier to evaluate and synthesize. To be more exact, each controller uses a local communication link to compute a control execution locally based on measurement, which is then returned to an actuator node to activate the system. This decentralized system computes local control executions within local controllers, reducing calculation cost and design complexity in contrast to the centralized configuration.

One major concern with the decentralized design is that inferior control performance may occur since each controller node lacks as much knowledge about the system's status or output as the centralized configuration. If the local control decisions are similar to the best global control decisions, then a decentralized design is more scalable in this regard. However, in wireless networks, where a large number of nodes synchronize their activities via communication networks, a lack of communication and support among decentralized controllers may result in poor system performance and limit the range of its applications.

Distributed configuration. It sets itself apart in two ways: (i) the plant is usually composed of many simple cooperating components (e.g., subsystems and agents); these are physically distributed and interconnected to coordinate their tasks and achieve a common goal; (ii) information about each subsystem is exchanged between system constituents (e.g., sensors, controllers, and actuators) via a shared communication network. These two qualities are principally responsible for so-called cooperative control. In this design, each controller can share its local additional information with all neighboring controllers to collect knowledge on plant dynamics, as illustrated in Figure 1 (c). As a result, distributed controllers can coordinate their actions by interacting with and receiving information from other controllers in their proximity. The advantages of this structure include modularity, scalability, and robustness.

The use of distributed control systems has gained popularity in the last several years. This is due to the centralized control structure's high computational costs as well as robustness and reliability difficulties. When there are frequent interactions between subsystems, the decentralized strategy's systems have poorer performance and stability margins. In a distributed control framework, local controllers receive additional feedback for achieving stability and performance objectives from the combined variables of interacting subsystems, all without the complexity and rigidity of a centralized control structure [12].

5. DISTRIBUTED CONTROL SYSTEM (DCS)

Computer software programs known as distributed control systems (DCSs) link with control devices and offer a centralized human-machine interface (HMI) for equipment control. This section discusses the evolution of DCS, its workings and operations, and its architecture in detail.

5.1 Evolution of DCS

The inception of DCS can be attributed to the 1960s and 1970s, during which the initial DCSs were developed for application in the petroleum and chemical industries. Honeywell and Yokogawa firms created branded hardware and software for the first DCS. They were mostly employed to monitor massive, intricate processes like chemical reactors and oil refineries in the chemical and petrochemical sectors. Subsequently, DCSs were introduced in the 1970s by aircraft and industrial process control, which made it possible to conduct remote control operations and sparked teleoperation research [13]. Powerful programmable logic controllers (PLCs) and supervisory control and data acquisition (SCADA) systems were among the new technologies introduced in the 1980s and 1990s, which helped advance and enhance DCS.

DCSs were also employed in a number of industries, such as manufacturing, water treatment, and power generating. With the introduction of new technologies like Ethernet and the Internet in the 2000s, which allowed for process management and remote monitoring, DCSs underwent significant evolution. In an effort to enhance process control and optimization, DCSs are increasingly incorporating complex control algorithms and data analysis features. Large-scale, complicated processes are currently operated by DCSs, which are acknowledged as the most cutting-edge and sophisticated control systems. They are employed in many different industries. The prominent brands manufacture of DCSs are as follows [14, 15]:

Siemens: It is a German multinational firm that manufactures widespread industrial automation and control solutions, including distributed control systems. Simatic PCS 7 is the name of their DCS.

Yokogawa: Multinational Japanese company Yokogawa produces DCSs, among other industrial automation and control technologies. They utilize a technology called CENTUM VP for data gathering.

ABB: Multinational Swedish-Swiss company ABB produces a wide variety of DCSs and other industrial automation and control systems. The ABB Ability System 800xA is their DCS.

Honeywell: A multinational company based in the United States, Honeywell produces a range of industrial automation and control solutions. Experion is their distributed control system.

Rockwell Automation: Manufacturing a range of industrial automation and control solutions is the US multinational company Rockwell Automation. PlantPAx is their distributed control system.

Schneider Electric: This international company, based in France, produces a range of DCSs and other industrial automation and control systems. Foxboro Evo is the name of their DCS.

Emerson: DCS DeltaV is provided by the multinational American company Emerson.

5.2 Working and operation

DCSs are comprised of several control devices, such as computers, sensors, and controllers, which are dispersed throughout a plant. Each device performs a specialized function, such as data gathering, storage, or process control. In DCS, every process has its controller located on-site. These local controllers are linked together through a local area network, allowing all controllers in the network to be monitored or reprogrammed from a single supervisory computer, as shown in Figure 2. Once coded, each process can operate independently.

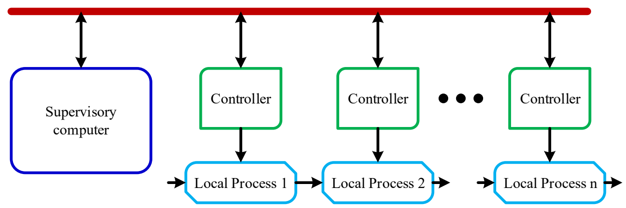


Figure 2 Distributed control system

A DCS enables each machine component to have its specialized controller to carry out the operation, as opposed to a centralized control system that oversees every unit. A factory's DCS is formed by a number of strategically positioned local controllers. A fast communication network connects these local controllers. A central supervisory control system is overseen by an operator when each controller functions independently. Distributing the control system architecture throughout the factory or plant allows for efficient control and process quality mechanisms. Furthermore, if a component of the DCS design fails, the plant will continue to work. Because of these benefits, DCSs are frequently used in industrial areas, including processing and manufacturing plants.

5.3 Structure and Architecture of DCS

Within the context of DCS, the control processing unit is scattered across the system's nodes, increasing system resilience and reducing the failure of a single processor. Figure 3 depicts each stage of the DCS structure. Flow elements, temperature sensors, and control valves are examples of final control components that make up level 0 field equipment. Distributed electronic processors and sophisticated I/O modules are included in Level 1. Supervisory computers at level 2 gather information from processing nodes in the system and show operator-managed panels. Rather than actively managing the process, Level 3, also referred to as the production-managed phase, involves assessing production and monitoring targets. Levels 1 and 2 are considered the operational phases of the whole DCS, in which all components are integrated into the systems of a single production personnel. In contrast, level 3 and level 4 manage the controlling and scheduling events [16].

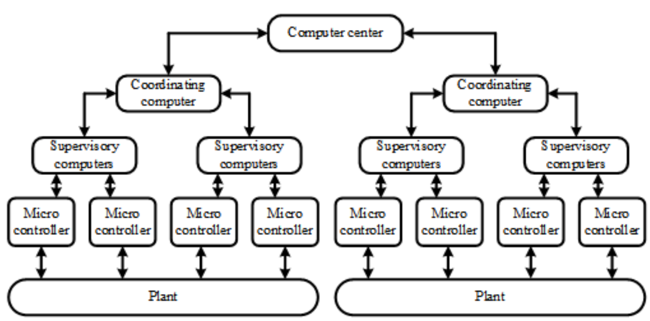


Figure 3 Structure of DCS

A DCS consists of four main components: an engineering workspace, an HMI or operating workspace, a process control unit, and communication media. Engineering Workspace elements function as the DCS' supervisory controller. The Engineering Workspace is made up of either a computer device or a personal computer that is preloaded with standard engineering software, such as the ABB freelancing DCS. This ABB freelancing DCS has been designed specifically for the control builder F engineering workstation. HMI is used for controlling, monitoring, and managing plant parameters. The local controlling unit, processing unit, or distribution controller is referred to as the Process

Controlling Unit in DCS. DCS relies heavily on communication mediums. This medium connects the engineer's workspace, process unit, operational section, and smart gadgets.

5.4 Important Features of DCS

In this part, the DCS's important features are discussed, including its capacity to manage complicated processes and specified function blocks, work on a scalable platform, and enable high-level HMI [17]. Figure 4 displays the main characteristics of DCS, which distinguish them from centralized systems.

- Managing complicated tasks: PLCs and other controllers are used in ICS to quickly control and regulate diverse industrial plants' processes and characteristics. As a result, complex calculations are efficiently performed by these systems.
- Pre-defined Functional Units: DCS has pre-defined programs and algorithms, making it easier to utilize for complicated problems and applications. A wide range of programming languages, including function block, ladder, and sequential, are supported by DCS. As a result, it allows the users to create custom programs to meet their specific needs.
- Scalable Platform: DCS systems are expandable based on the amount of connected I/O devices. It increases the number of input-output devices and servers to accommodate more users.
- Advanced HMI: HMIs from DCS give users the ability to monitor, manage, and modify any process as needed. It shows the graphical and numerical performance of the system, allowing the operator to utilize the data and adjust the plant's settings as needed.

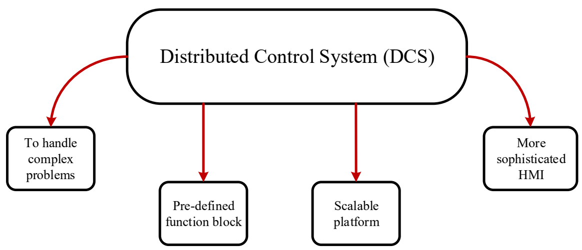


Figure 4 Features of DCS

6. APPLICATIONS OF DCS:

In many industrial and infrastructure applications, distributed control systems, or DCSs, are utilized to automate and regulate complex activities. Many businesses, such as power plants, water and sewage treatment facilities, chemical manufacturing facilities, refineries, and pharmaceutical processing facilities, employ DCS to regulate production systems inside the same physical location [18].

6.1 Industrial control system

There are various types of ICSs, including SCADA systems and DCSs [19]. Figure 5 shows the three layers of ICS: corporate network, logic control, and physical control. Managers can access a supervisory computer or a human-machine interface (HMI) remotely from the corporate network layer. Using an HMI or a cloud-based supervisory computer, the logic control layer's system administrators (SCADA/DCS) monitor production status and issue commands to modify the control sequence. All control devices (such as PLCs and sensors), protocols (like Modbus and Distributed Network Protocol version 3 (DNP3)), and production locations are included in the physical control layer. Fault detection with a Full-scope Simulator based on State Information Imaging (FDFSSII) was integrated into a DCS by Yao et al. [19], and it functions as the nuclear reactor plant-wide fault detection system.

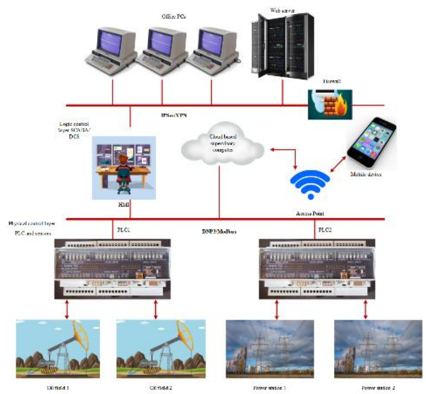


Figure 5 An Overview of an Industrial Control System (ICS)

6.2 Power generation

Nuclear, gas, and coal power plants, as well as other power generation processes, are regulated and monitored in large part by DCSs. In order to guarantee that the power plant operates safely and efficiently, they are used to control and monitor process parameters, including temperature, pressure, flow, and level. DCS is referred to as the "brain" of nuclear power facilities due to its importance in nuclear safety. DCS is designed especially for nuclear reactor equipment, enabling post-accident monitoring and safe shutdown in dangerous environments. It also plays a crucial role in the stable operation of nuclear power plants. The power supply system is crucial for supplying electricity to the DCS so that it can work properly. Hongpeng et al. [20] investigated the design requirements of a DCS power supply system in nuclear power plants using IEEE, IEC, and other standards. This study also presented a revolutionary, highly dependable power supply method for DCS systems based on existing equipment manufacturing technology. By minimizing the conversion process on the distribution path, improving the design of cross-ties between divisions, and maximizing the advantages of a DC distribution system, this concept boosted the distribution system's stability, flexibility, and dependability.

One essential part of the DCS is the emergency shutdown (ESD) system, which is frequently built with many redundant channels for greater reliability. The reliability of an ESD system with a 2oo3 structure, two out of three units required for the system to function, was examined by Guo et al. [21]. The ESD system employed a three-channel parallel arrangement with mutually firing protective subgroups. The passivated implanted planar silicon (PIPS) controls and separates the signals that are obtained on-site, as seen in Figure 6. Subgroups receive these signals and use 'or' logic operations to generate the channel-level protection signal for the reactor trip breaker (RTB).

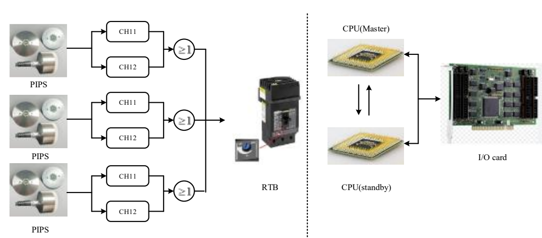


Figure 6 ESD system with 2oo3 architecture and protective channel system composition

One of the most difficult and intricate nuclear power station upgrading projects is modernizing the control room. It can have a substantial impact on operations, particularly turbine replacement. Hugo et al. [22] modified the control room by changing from an analog to a digital control system. The purpose of this migration was to replace certain older analog controls on the control boards with their digital equivalents in the DCS. By enabling operator control stations to service various systems, this DCS migration has improved system reliability and streamlined control room operations.

The combustion of boilers in coal-fired power stations releases a great deal of nitrogen oxides (NOx), which contribute to a number of environmental problems. Coal-fired power plants traditionally used DCS to monitor and manage plant parameters. Yuan et al. [23] created a system that predicts NOx emissions from coal-fired power facilities. DCS gave historical data under changing conditions. They also used principal component analysis (PCA) and mutual information techniques to determine which auxiliary variables were most closely connected with inlet NOx emissions. Finally, a stacked-generalization ensemble approach has been applied to predict NOx emissions.

Tang et al. [24] employed DCS and Supervisory Information Systems (SIS) to regulate thermal power facilities. Initially, the DCS sensors collected NOx emission data in real time at a number of monitoring stations before sending the written data to the SIS system. The analytical platform included a Decision-Making model that used data obtained from the SIS to determine the current operational state. It is then delivered to the related prediction model, which makes predictions based on the operating condition. In order to control the injection of ammonia, the PLC relayed the anticipated outcomes to the SIS system. A DCS approach to reducing NOx emissions from a class of diesel engines has been presented by Lei et al. [25]. This DCS method made use of a network of diesel engine test benches working in unison, with each engine linked to its own DCS machine that had an SCR device. All DCS units received regulatory measures from the central processing unit (CPU). The findings demonstrated that the DCS was effective in limiting NOx emissions to levels specified for the specified engine group but also demonstrated strong economic performance by optimizing NOx conversion efficiency distribution and using a cost-effective urea injection dose. The DCS emission control system was well-suited for use, with several diesel engines operating in parallel under varying loads and speeds.

Using a subcritical coal-fired power plant model, Kestering et al. [26] compared conventional and advanced control strategies in relation to Industry 4.0 infrastructure across different operational scenarios. Part of this setup was a data analytics system, a power plant model, and online load demand and DCS integration. The Process Unit was linked to the PI Server-managed HMI, DCS, and Process Database & Advanced Analytics via Matrikon® OPC Server. The intricate dynamics of the system's variables were taken into account when designing a control structure that integrates conventional methods of proportional-integrative-derivative (PID) with model predictive control (MPC). The DCS level was the site of the implementation of this control framework. Data was received by the controllers from the processing unit, and control moves were computed and sent back over the Matrikon® OPC Server. Among the variables that can be controlled are the following: electric power, drum pressure, level of the drum, temperature downstream of the primary desuperheater, and temperature downstream of the final superheater.

Choi et al. [27] suggested a practical air-to-fuel ratio (AFR) management with one-step forward control, which eliminates the requirement for online optimization and allows for direct application in thermal power plants using current DCS. DCS system resources must be properly managed to ensure the power plant system's reliability. A new strategy for DCS maintenance must be implemented in a systematic way to ensure dependability and risk management under controlled settings. By quantifying equipment risk using the reliability technique and analyzing the implications of failure, the DCS system executes risk-based maintenance [28]. Table 1 summarizes the significance of DCS in power generation applications.

Table 1 Summary of different plants with DCS in power generation applications

Reference	**Plant**	**Purpose**	**Contribution**	**Advantages**
Hongpeng et al. [20]	Nuclear power plant	To examine the Distribution design needs of the DCS power supply system	Utilized matured device manufacturing technology.	Improves the dependability, constancy, and flexibility of the distribution system
Guo et al. [21]	Nuclear power plant	To model emergency shutdown (ESD) system for DCS.	The channel-level protection signal was generated using a three-channel parallel architecture.	Avoided the reactor trip breaks.
Yuan et al. [23]	coal-fired power plants	To control the NOx emissions	Stacked-generalization ensemble approach	Reached the highest correlation coefficient based on DCS's historical

				data under varying situations.
Hugo et al. [21]	Nuclear power plant	To modernize the Control room.	Removed analog devices from the control boards	Guaranteed an integrated result and offered a notable enhancement in operator performance.
Tang et al. [24]	Thermal plant	To forecast NOx emissions	Long Short-Term Memory (LSTM)	Enhanced prediction accuracy by training different sub-models for different operating states.
Lei et al. [25]	Diesel engine group	To deal with NOx emissions	A selective catalytic reduction	The DCS emission control technology can be used for several diesel engines operating in parallel with different loads and speeds.
Kestering et al. [26]	coal-fired power plants	To control temperature, electric power, pressure, and drum level	Industry 4.0 infrastructure, PID, and MPC controllers.	Achieved good performance in power plant cycling applications
Choi et al. [27]	coal-fired once-through power plants and oil-fired drum-type power plants	Air to fuel ratio (AFR) control	One-step ahead control	Real-time optimization is not necessary, and it is quite basic.

6.3 Oil and gas

Drilling, refining, and petrochemical production are just a few of the oil and gas sector operations that DCSs are used to control and monitor. In order to ensure the efficient and safe functioning of industrial processes, DCS is used to monitor and control process variables, including pressure, flow, and level. Mahmood et al. [29] provided details of an Internet-based DCS that uses a regular web browser to track real-time data in oil refineries. The central server, which functions as the system web server, has been connected to each DCS. The developed system in this work was tested using the North Oil Refineries of Baiji (NORB) in northern Iraq as a case study. These refineries have twelve discrete DCSs connected in a mesh network to create a single unit that resembles a standard SCADA. NORB used a Yamatake DCS, whose structure is given in Figure 7.

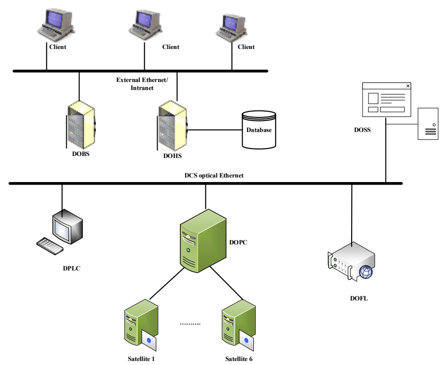


Figure 7 Northern Iraq's North Oil Refineries of Baiji (NORB) with DCS

Dependable Object Linking and Embedding (DOPC) is a brand of Yamatake OPC that refers to the communication of real-time plant data across control devices from diverse suppliers. A copy of real-time data has been saved to the DEO Open History Server (DOHS). DOHS was considered a local web server that served an external client. Yask et al. [18] investigated the available malware detection and security solutions for DCS, focusing on the Oil and Gas sectors. Currently, distributed control systems are installed in every liquefied natural gas chemical facility. The requirements of urban natural gas operators, however, cannot be met by the conventional control system. This is mostly due to variations in natural gas pressure at the intake and exit of LNG plants, which vary with the city's gas load. The DCS is unable to adjust production conditions automatically in response to pressure changes. To solve this problem, Feng et al. [30] created an improved system that automatically controls working conditions based on the pressure of the gas source.

Bellini et al. [31] used Snap4Industry's IoT development platform and framework to operate and monitor complex facilities with various DCS and chains in accordance with Industry 4.0 concepts. These new skills were used to provide higher levels of control at ALTAIR, a large chemical complex in Italy. Altair Chemical was the first chlor-potash facility in Europe to produce KOH without utilizing mercury. The goal of the ALTAIR SODA-4.0 project is to optimize the processes involved in the generation and consumption of hydrogen and chlorine while developing and implementing an integrated management system. Its foundation is a brand-new industrial setup centered on a production facility for caustic soda, or NaOH. In order to reduce energy use, increase productivity, and enhance safety, Snap4Industry has played a key role in developing an automated system that combines data from the DCS and the business management system. The technology enables flawless coding while eliminating human errors and oversights.

The conventional industrial control infrastructure in petrochemical facilities has been PLC or DCS-based. The Safety Instrumented System used in Saudi Arabian petrochemical plants connects with the DCS via a single channel. Therefore, no vulnerability may be introduced into the SIS through this channel. Blockchain technology is utilized to manage control and data in DCS [32]. Mazur et al. [33] compared the advantages and disadvantages of PLC and DCS-based systems for petrochemical applications. A data-driven model architecture incorporating prediction, production pattern clustering analysis, and feature subset selection (FSS) was described by Li et al. [34]. This framework is developed to estimate ethylene yield in ethylene plants using vast sensing data captured by the DCS of petrochemical firms.

Shayeghi et al. [40] presented a hybrid supercapacitor-battery energy storage system (SC-BESS) in a wind-diesel system to regulate system transients efficiently. For active power management, this system used a fuzzy-type DCS. It also employed a novel online intelligent strategy to reduce control system design work and achieve optimal tuning by merging fuzzy logic with DCS using particle swarm optimization approaches. This mechanism combines the flexibility of DCS with the features of online fuzzy theory.

6.4 Water treatment

Water treatment operations like filtration, desalination, and wastewater treatment are controlled and monitored by DCS. They keep the process safe and efficient by managing and monitoring factors, including flow, pH, and temperature. Table 2 summarizes the use of DCS in water treatment and oil and gas applications. For the purpose of fine-tuning control parameters in seawater desalination with a DCS-interfaced conical tank system, Murugan et al. [35] proposed a CDM-PID control methodology. This controller has been used in a desalination plant to avoid excessive chlorine gas leakage. Here, an ethylene-ter-polymer (ETA) distributor was used to inject a 10% NaOH solution into the top of the scrubber column, distributing it evenly across the packing. An extensive discussion of methods for removing and separating oil from water and wastewater is given in this publication. It provides a summary of the sources and types of oil found in wastewater, including man-made and natural sources, as well as the differences in physical states of the oil, such as dissolved, emulsified, and free oil [46].

Table 2 Summary DCS in water treatment, Oil and gas applications

Reference	Plant	Purpose	Contribution	Advantages
Mahmood et al. [28]	Oil Refineries	To accomplish real time monitoring and control	Three-tier client-server model	Able to use open standards to connect a huge number of industrial DCSs.
Bellini et al. [31]	chemical plant	To control the processes of hydrogen and chlorine invention and consumption	Snap4Industry	Execute procedures with the highest level of safety.
Li et al. [34]	Petrochemical industry	To predict the ethylene yield of an ethylene plant	FSS and production pattern clustering analysis	It possesses a modular structure and a significant capacity for generalization.
Feng et al. [30]	Liquefied natural gas chemical plant	To control the production level based on the pressure fluctuation	Decreased the expansion machine's frequency in order to improve the automated control system.	Enhanced production efficiency The failure rate is minimized.
Murugan et al. [35]	Desalination plant	To control the excess chlorine gas leakage	CDM-PID control	There will be less oscillation and less time for settling.
Shayeghi et al. [40]	wind-diesel system	To regulate the system's transient	A fuzzy type DCS, and DOFCS	Effectively managing the system's dynamics of frequency and voltage and enhancing the wind-diesel hybrid system's power quality.

6.5 Distributed Control of Microgrid

A DCS can help improve microgrid controls, which are different from traditional power systems. A microgrid (MG) is a network of distributed energy supplies and interconnected loads that functions as a single, controllable unit in relation to the wider power grid. Distributed control methods are used in conjunction with centralized and decentralized controls to ensure that the system works reliably within and between microgrids [35-36]. It is anticipated that distributed control will respond far more quickly than centralized control but more slowly than decentralized control. Moreover, as demonstrated in Figure 8 [37], distributed control can employ local coordination to stabilize the system and bring the operational states of distributed energy resources closer to the intended values. On the other hand, control oscillations might be readily introduced during the convergence phase.

The integration of those reasonably priced and economical resources into the energy mix at the consumer level was the main focus of recent MG research trends. Distributed control (DCT) systems for alternating current, direct current, and hybrid MGs have been the subject of numerous research endeavors due to the intricacy of DG integration into the MG [43]. Proponents of this approach assert that distributed controllers offer a number of benefits over centralized and decentralized control methods, including increased reliability, flexibility, controllability, the ability to initiate operations independently, and resilience to communication failures.

In their thorough analysis of distributed and decentralized control techniques for microgrids, Sarathkumar et al. [44] emphasized the importance of these approaches in facilitating resilience, scalability, and robustness. The shift from centralized to decentralized paradigms is the main topic of discussion, along with important strategies, including primary, secondary, and tertiary control layers. In order to optimize power sharing, voltage regulation, frequency stability, and energy management in islanded and grid-connected modes, the paper investigates the use of sophisticated algorithms such as multi-agent systems (MAS), consensus-based control, and artificial intelligence (AI).

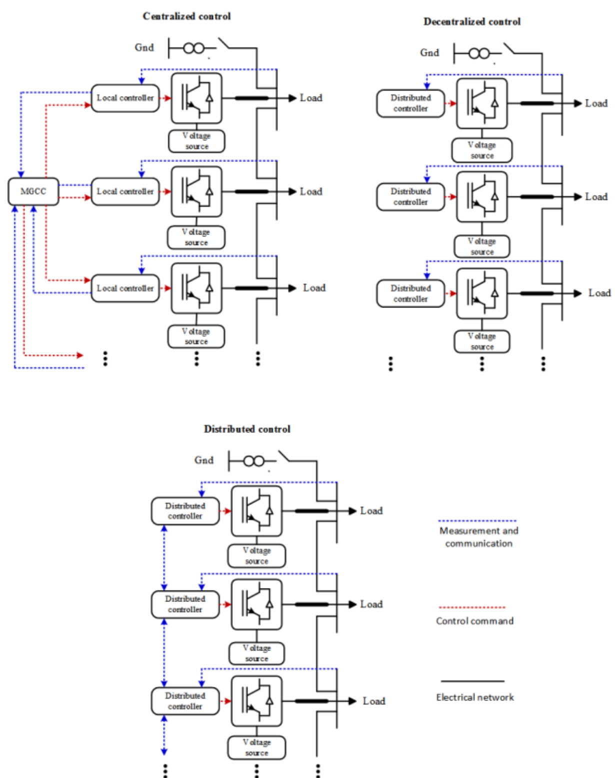


Figure 8 Standard island microgrid control architectures: centralized, decentralized, and distributed

A DCS allows operators to monitor the status of the entire microgrid from a single location [38]. Figure 9 displays an overview of a DCS communication network deployed in an off-grid microgrid, such as an island agreement. As seen in Figure 9, the DCS is responsible for interfacing directly with all energy producers. A number of power plants are required to provide the island's electrical demands. This microgrid contains energy manager software on a separate server, which receives all necessary data from the DCS and reports all calculation results back to the DCS. The DCS communicates with all real power producers. The DCS provides centralized monitoring and control. It's worth mentioning that the energy manager could be integrated into the Distributed Control System (DCS) rather than be a unique standalone unit, as shown in Figure 9.

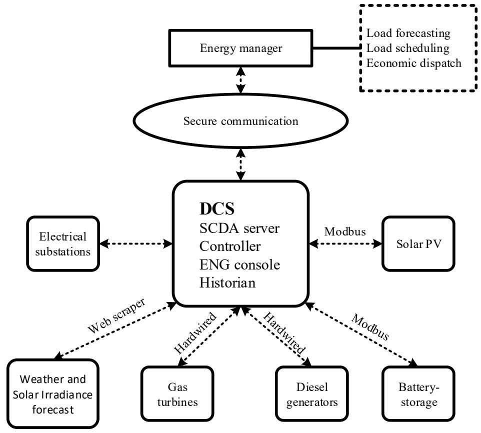


Figure 9 Communication network of DCS in off-grid microgrid

To better manage microgrids, Srikanth et al. [39] proposed a new centralized Supervisory Control and Data Acquisition System in conjunction with Distributed Control Systems, driven by the aim of increasing the use of SCADA systems in microgrids. The main control system issues directives to the subsystems, and the local controllers are in charge of implementing control schemes that are specific to those subsystems. An interconnected sensor network keeps an eye on critical metrics, while a graphical user interface (GUI) shows the current state of operation and parameter values for different subsystems in real time.

7. STABILITY ANALYSIS OF DCS

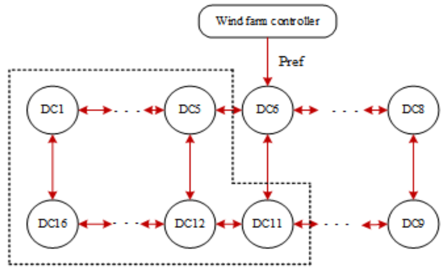
Stability analysis of a control system is usually done by analyzing the system's transfer function or state-space representation. The quality of input data, which must be sent precisely and promptly, determines the output of any distributed process, including DCS, which consists of numerous independent processes. The emergence of large-scale systems with interacting subsystems can be attributed to economic causes and technological improvements in manufacturing and industrial processes. There are a lot of obstacles to overcome while doing stability assessments and designing appropriate controllers for such complicated systems. To achieve stability and performance goals without the complexity and rigidity of a centralized control structure, the linked variables of interacting subsystems provide local controllers with additional feedback in a distributed control architecture [45].

7.1 Linear matrix inequality based analysis

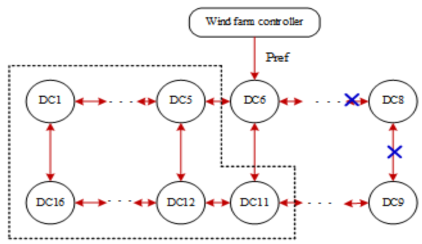
The DCS contains Discrete-time subsystems that are coupled by their states. Every subsystem has a local controller. Random packet loss and random latency occur in the non-ideal communication network connecting local controllers of interacting subsystems. In order to counteract these negative consequences, a model-based control technique is applied, which estimates the states of interacting subsystems for adjusting the local control laws and ultimately stabilizes the system. In this approach, DCS is represented as time dependent impulsive system. Next, a new algorithm is presented to assess the interaction between the subsystems. This algorithm is used by all local estimators to offset the detrimental impacts of packet loss and time delay on the stability and performance of the closed-loop system. After that, a conventional linear matrix inequality (LMI) based condition is used to generate and analyze a quadratic Lyapunov function. In [12], a design guideline for creating a stabilizing controller for every subsystem is provided.

7.2 Convergence Stability

Using convergence speed, Gao et al. [41] examined the stability of the distributed control method for large-scale wind farm active power regulation. To ensure the stability of convergence of a communication network, the transition weight matrix of distributed controllers in this system must be precisely specified. The convergence analysis of a wind farm collaboration system is depicted in Figure 10. DCs in group I work together with other DCs in Group II through KESS management, as shown in the dashed block, to achieve the necessary generation during regular operation. The power reference that was initially obtained by the main controller of the wind farm is given to the leader DCs in group II. The second example, a communication breakdown in the internal subclass controller, is shown in Figure 10. Under such circumstances, the communication-failed DC (DC8 in Figure 10) reverts to MPPT operation mode and aggressively isolates itself from the external communication topology. Similarly, because of their unregulated nature, these DCs are categorized as Group I. In this instance, reference creation is distributed among the recently established Group II.



(a)



(b)

Figure 10: DC mesh topology in a large-scale wind form for (a) regular operation and (b) when a DC's internal communication fails

7.3 Quadratic stability

The quadratic stability of the DCS is investigated by reducing the dynamic allocation's quadratic performance index [42]. The DCS constraint also includes a restriction on control energy for each subsystem. One method for calculating the parameters offline is to solve a series of linear matrix inequalities (LMIs). Moreover, the primary determinants of the closed-loop stability of the DCS are the upper-level control rule and the dynamic control allotter. The allocation process is kept quadratic stable by the dynamic control allocation technique. Carefully crafting the upper-level control law that uses the allocation error signal to stabilize the closed-loop model is required to attain closed-loop stability. However, there are a number of established methods for preserving closed-loop stability, including passivity-based control theory, robust control theory, sliding mode control, D-stability design, and the small gain theorem.

8. ADVANTAGES AND LIMITATIONS OF DCS BASED CONTROLLERS

The advantages and limitations of DCS are mentioned here:

- Complex structures: A DCS can access a huge number of data in a complex environment rather than comparable PLCs.
- Scalability: Whenever more control or process units are required, the I/Os can be extended by adding more I/O modules to a controller.
- Improved process control: PID control is one of the complex control algorithms that DCSs use to deliver precise and accurate process management.
- Remote access: Process monitoring and control is enabled by the DCS, which allows remote access via a computer or mobile device.
- Redundancy: Controllers and servers are examples of redundant components commonly found in DCSs that increase system reliability and reduce downtime.
- Flexibility: DCSs are compatible with a wide range of input and output devices and can be easily configured to control various operations.
- Better data gathering and analysis: Large volumes of process data that can be utilized for analysis and process enhancements can be gathered and stored by DCSs.

- ❖ Improved safety: Process security can be improved by integrating security interlocks and alerts using DCSs.
- ❖ Integration: To provide a complete control and monitoring solution, DCS can be easily connected to other systems, including SCADA, PLC, and MES systems.
- ❖ Simple Maintenance: The modular design of DCSs makes it easy to replace, upgrade, and maintain individual system components.

However, DCS also has some disadvantages, including:

- ❖ **Software development:** Software development expenses may rise due to DCS.
- ❖ **Failure diagnosis:** The failure diagnosis in DCS is more complex than in other controllers.
- ❖ **Communication technology:** Communication technology is needed for DCS.
- ❖ High initial cost: DCSs can be expensive to purchase, install, and maintain.
- ❖ Complexity: Due to its complexity and large number of moving components, DCSs can be challenging to comprehend and maintain.
- ❖ Training: Operating and maintaining DCSs requires specific training, which can be expensive.
- ❖ Dependency on software and hardware: Due to hardware and software dependency, DCSs are susceptible to hardware malfunctions and software errors.
- ❖ Network dependency: Networks are necessary for DCSs to enable communication between servers and controllers. The system will not work as a whole if the network is down.
- ❖ Limited compatibility: Integrating DCS into current processes can be challenging because they are incompatible with other systems.
- ❖ Limited scalability: As a process grows, certain DCSs may be difficult to expand due to their limited scalability.
- ❖ Restricted data visualization: Analyzing and understanding process data can be challenging for DCS because sophisticated data visualization capabilities may not be available.
- ❖ Restricted mobility: Due to their limited mobility, some DCSs may struggle to access and manage the system remotely.

9. FUTURE RESEARCH OPPORTUNITIES

Although DCS updates demand more thorough research and meticulous procedures, the benefits will make the original effort even more worthwhile. Upgrading DCSs based on current architectures without causing major disruption to operations is a difficult issue. In the future, DCS will address this challenge by becoming more open, flexible, and digital. The goal is to establish a more modular design that allows users to improve the DCS without interfering with the workflow by distinguishing between vital DCS tasks and those that are less time- or process-critical.

- ➢ The new DCS structure aims to establish its own maintenance and optimization layer, providing users with easier data access and analysis to improve the organization’s business operations.
- ➢ DCS customers must deploy new, faster DCS solutions online to achieve their business goals while using fewer resources. One approach is to split the software development and automation hardware during the setup phase.
- ➢ By combining digital technologies with the DCS, users receive more automation, openness, and flexibility. It will pave the way for significant increases in productivity, quality, speed, and process availability.
- ➢ Even though low-level operations are already automated, higher-level decision-making is still primarily done by humans. These complex decisions can be made by machines due to the advancement of machine learning and AI techniques. Technicians can access real-time process conditions and activate control systems via mobile devices to diagnose and resolve problems.
- ➢ Distributed systems are further enhanced as AI paradigms and the larger IT environment enable the development of intelligent, reconfigurable manufacturing machines and systems.
- ➢ It is possible to implement augmented reality (AR) solutions that allow users to access virtual instruction manuals and tutorials or provide the ability to carry out repairs with professional assistance. They can share views of devices or situations with their colleagues and overlay digital images on top of real views of the devices.

10. CONCLUSIONS

Distributed control solutions are necessary for the automated operation of large and complicated process networks, which are essentially linked networks. For this kind of deployment, DCS is regarded as a crucial technology. It is typically defined as a reusable software layer that stands between the operating system and distributed applications. Therefore, this study briefly discussed the general configurations of control systems and their work processes, architectures, and essential features of DCSs. Additionally, the applications of DCS in industries such as power plants, refineries, water and wastewater treatment, pharmaceutical processing and facilities, and chemical manufacturing facilities are discussed. In addition, the advantages and contributions of each existing method in various applications are tabulated. The basic stability analysis of DCSs in various applications is then discussed. In addition, the advantages and limitations of DCS-based controllers are examined. Finally, some possible future directions of DCS in different sectors are suggested.

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